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DESIGN CONSIDERATIONS FOR A FROZEN BLOOD SHIPPING CONTAINER USED IN THE TRANSPORTABLE BLOOD TRANSSHIPMENT CENTER PROGRAM

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A standard rectangular-shaped shipping container capable of accommodating up to 24 packs of red blood cell solution was shown to be suitable for blood storage and transport. The ability of the unit to maintain RBC packs in the desirable and acceptable temperature range was demonstrated using an insulated box coupled with a coolant.

The unit's size (.54m X .54m X .52m) (21.5" X 21.5" X 20.5") and weight (31.2 kg) (68.4 lb) make it easy for one individual to carry; yet is strong enough to survive many trips and inexpensive enough to be discarded.

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DESIGN CONSIDERATIONS FOR A FROZEN BLOOD SHIPPING CONTAINER USED IN THE TRANSPORTABLE BLOOD TRANSSHIPMENT CENTER PROGRAM

INTRODUCTION

Since modern blood component therapy was introduced, red blood cells (RBCs) have largely superseded whole blood in most blood banks. Techniques are now available by which red blood cells may be frozen and stored for prolonged periods at very low temperatures. In the most widely used method, glycerol is added to prevent red cell damage during freezing and thawing. After thawing, the glycerol is washed out to prevent osmotic damage to the red cells. The cells may then be infused with saline, albumin, or plasma. Posttransfusion survival of such red cells has been shown to be satisfactory (1).

Along with the growing interest in freezing blood, there is a critical need for special shipping containers and packaging techniques to protect the blood during long distance shipping even under extreme temperature fluctuations.

Blood must be frozen during transportation for maximum retention of quality. Permanently attaching a mechanical freezer to a blood shipping container may not be desirable for several reasons: increased weight; reduction in usable volume; availability of power; and rejection of heat produced by the condensing unit. Therefore, design criteria for containers for blood and blood components must consider weight, size, thermal performance, and mechanical protection of the contents.

It was not until World War II, with the urgent need for banked blood in multiple areas, that practical shipping containers for refrigerated liquid blood evolved (2). Moreover, the increasing use of air transportation for distributing perishable commodities has also focused attention on quality assurance in transit. Actual refrigeration is not available in cargo aircraft nor in the cargo compartments of passenger aircraft; therefore, proper transit temperatures are provided by precooling the blood and using suitable insulated and refrigerated containers. Accordingly, a wide variety of shipping containers were designed and employed by commercial vendors, as well as by the Armed Forces. These included food containers, wooden boxes, insulated plywood chests, and fiberboard cartons. The containers were generally rectangular in shape and were merely designed for temperatures between -10 and 20°C. Ice (solid, chopped, or flaked) was used to refrigerate blood in transit. Dry ice was used extensively with frozen products, the amount used depended on the type of container and the length of the journey. However, without proper ventilation, the use of large amounts of dry ice may cause an accumulation of carbon dioxide gas in concentrations dangerous to man.

In the past, the most widely used shipping container for refrigerated blood was a light weight, reinforced cardboard container developed by the Army at Fort Totten, New York. This container was eventually replaced by a three-piece, Styrofoam box with suitable thermal and structural characteristics.

Several investigators have studied the conditions encounter-

ed in the transportation of whole blood using a container similar to the Styrofoam shipper. The latest design is a solid weatherproof fiberboard box insulated with polystyrene foam. This container can be used to ship refrigerated blood with conditioning medium.

Wet ice has been the common coolant used in these containers to maintain whole blood at 4 to 10°C during transit. A chemically produced refrigerant was developed by McPeak and Camp (3), that provided a satisfactory substitute for wet ice. An advantage of this type of coolant is that it may be produced without electricity, an especially important consideration during disasters and power failures.

The Military Blood Program Office (MBPO) is now implementing a worldwide frozen blood and blood components system, in which RBCs are stored at -80°C and preserved during shipment. This system uses new storage and shipping technologies without use of dry ice as a coolant due to its quantity restrictions on Military Airlift Command (MAC) aircraft. Several investigators and organizations have designed shippers for frozen blood products. Among the new designs, a collapsible/reusable container manufactured by Comedica Corporation appears to have some attractive features (4).

The purpose of this study was to determine the effectiveness of a frozen RBC shipment box for use in the Transportable Blood Transshipment Center (TBTC) program, subject to the following provisions:

- RBC units should be preserved below -40°C when removed from a -80°C freezer and subjected to external temperatures of -23 to 48°C for a period of 48 hours.

- Each container should be light enough for one individual to carry.

- Solid carbon dioxide (dry ice) or any other refrigerant /coolant with quantity restrictions on MAC aircraft, and externally powered refrigeration systems are prohibited.

A number of commercially available shipping containers were evaluated for general design characteristics and suitability for frozen blood storage. However, a rectangular-shaped container similar to standard, commercially available shippers was selected due to its availability and suitability to ship frozen blood as well as refrigerated blood.

MATERIALS AND METHOD

The container design features a rectangular-shaped box consisting of an inner and an outer shell, an insulating material, and packaged coolant.

Inner/Outer Shell -- The inner/outer shell (Fig. 1) consists basically of two 275 pounds (minimum) test, laminated fiberboard boxes assembled with water resistant adhesive for durability and longer life. During assembly, the inner shell is positioned in the center of the outer shell to create a space which is filled with insulation to form a one-piece box.

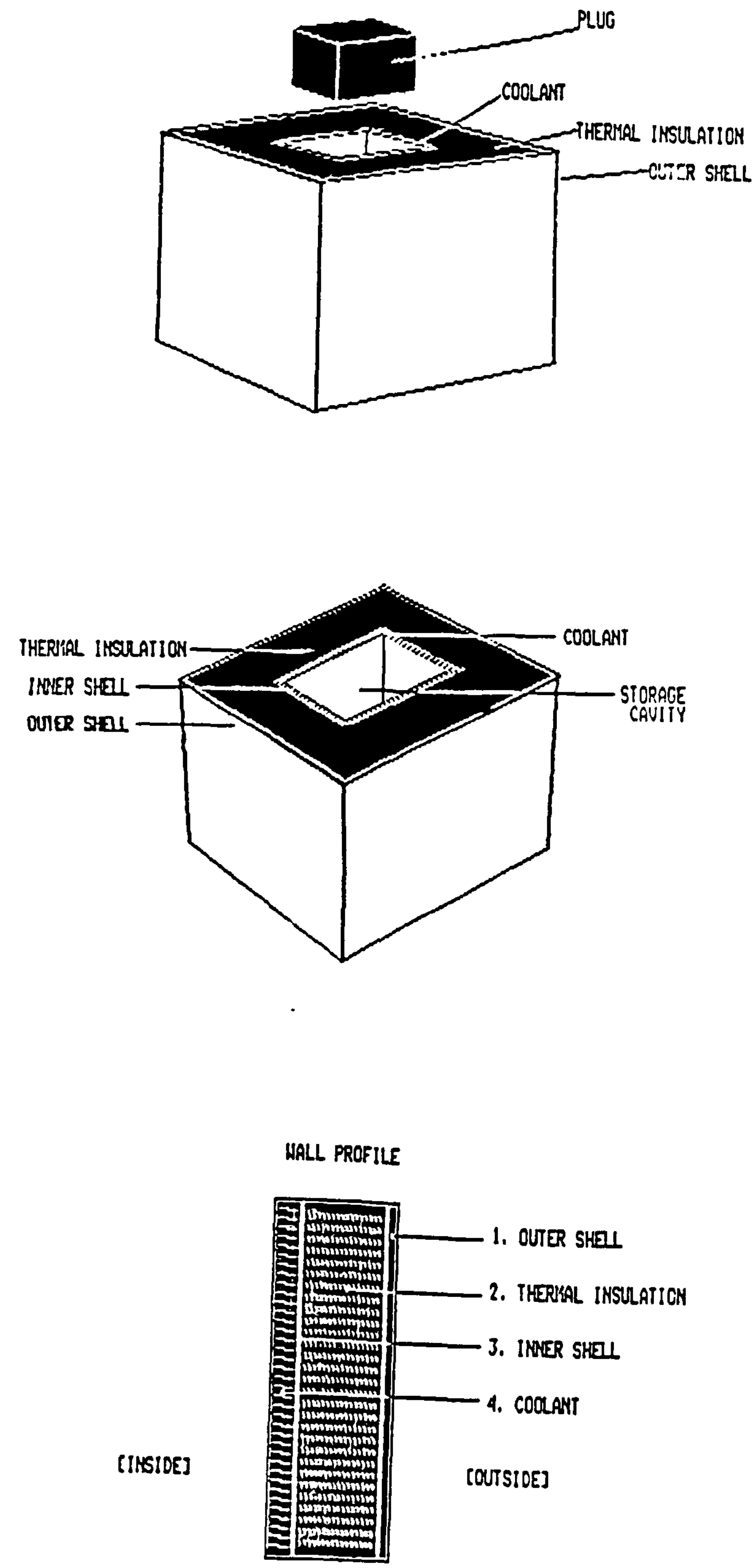


Figure 1. Schematic Diagram of Frozen Blood Shipping Container.

Performance and load-testing consisting of vibration, impact, and compression tests must be used to uncover potential package design deficiencies that may cause blood spoilage or impair the handling properties of the container. Any deficiencies revealed during testing must be corrected prior to the actual design.

Insulation -- Many types of insulating materials, individually or in combination, have been studied. Factors influencing selections are thermal conductivity, specific heat, density, permeability, cost, moisture effects, vibration resistance, ease of handling, temperature suitability, and strength. The thermal diffusivity factor, a function of conductivity and specific heat, is quite important when rapid temperature changes are anticipated. Low thermal diffusivity values combined with low thermal mass will permit more rapid temperature changes for the same system capacity. Commonly used materials include foamed polyurethane and polyisocyanurate, expanded polystyrene, rock wool, foamed rubber, cork, and other polymers. Physical characteristics of most of these materials can be found in reference 5.

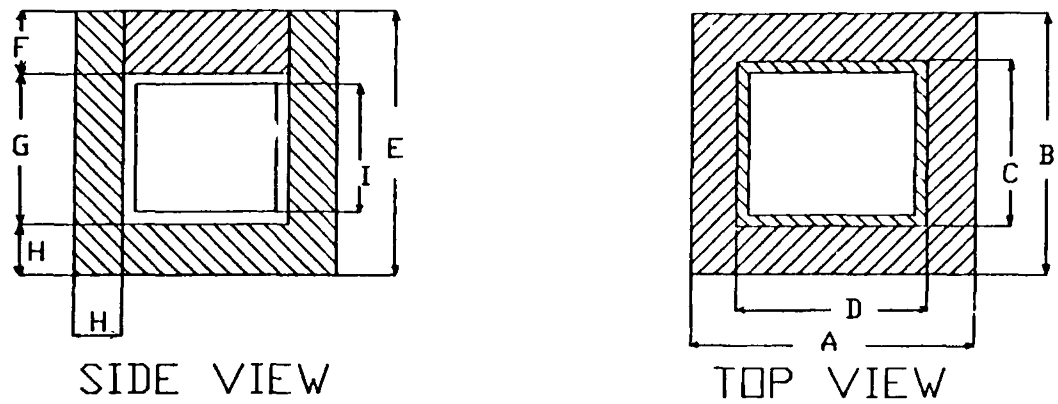
Of all these materials, foamed polyurethane appears to have superior properties as an insulation for frozen blood shipping containers. It is a rigid, closed cell foam with density dependent properties. Its physical properties increase with increasing density. Thermal conductivity of polyurethane is less than 0.023 W/m.$^{\circ}$C (0.16 BTU in/hr. ft^{2}.$^{\circ}$F) at a mean temperature of 24°C, for densities greater than 24 kg/m^{3} (1.5 lb/ft^{3}). The polyurethane foam core is then bonded to the inner and outer fiberboard shell to form a box of unitary construction. A poly-

urethane foamed plug prevents air exchange and minimizes heat loss (Fig. 1, 2).

Coolant -- As previously indicated, the use of solid carbon dioxide (dry ice) as a conditioning medium, due to its quantity restrictions on Military Airlift Command (MAC) aircraft, is prohibited. Therefore, there was a need to develop a coolant that could be used on MAC aircraft.

The absorption of low temperature thermal energy in the form of latent heat of fusion has been studied over the past several years. The so-called "latent heat" storage/absorption is accomplished by phase transition caused by heat exchange during which the temperature of a medium (coolant) remains unchanged. The total amount of thermal energy that can be absorbed by a mole of a certain medium is, to a large extent, determined by the amount of heat involved in phase transitions such as solid-solid, solid-liquid, and liquid-gas. The change from one phase to another occurs at different temperatures for different materials. Choice of the type of phase change and of materials enables this method of heat absorption to be suitable for frozen blood shipping containers over the wide temperature range of -80 to -40°C. The fact that the heat transfer through the coolant is both in the form of sensible and latent heat results in a higher heat absorbing capacity as well as smaller size and lower weight per unit of storage.

There are many factors that must be considered in selecting a coolant as a conditioning medium for the shipping container.



SCHEDULE OF DIMENSIONS

A	B	C	D	E	F	G	H	I
54	54	34	34	52	12.5	27	10	32

All dimensions in Cm.

Figure 2. Schedule of Dimensions.

The fundamental criteria for this phase-change coolant are as follows:

- The coolant should have a melting point in the range of $-80^{o}C$ to $-40^{o}C$ to permit desired heat transfer to take place.

- The coolant should have a large heat of fusion. The larger the heat of fusion, the less material is required to absorb a given amount of energy.

- The coolant should be nonsublimating, noncombustible, noncorrosive, and nontoxic. In general, the coolant should not be hazardous. Since the possibility of accidental leakage is always present, it is preferable to choose a material that has a neutral pH.

- The coolant should have a congruent melting point. The material should melt completely so that the liquid and solid phases are identical in composition. Otherwise, the difference in densities between solid and liquid will cause segregation, which causes changes in the chemical composition of the material.

- The coolant should be chemically stable in thermal cycling.

- The coolant should have high specific heat.

- The coolant should have a vaporization temperature above $150^{o}C$, for packaging purposes.

The technical literature indicates that a large number of organic materials will satisfy most of the above criteria, though special packaging may be needed (7,8).

Of all the suitable materials, n-Nonane, with a melting temperature of -53^{o}C, seems to be a good choice. The latent heat of fusion of n-Nonane is 120.62 kj/kg; therefore, it is recommended that n-Nonane be blended with other suitable materials with higher latent heat capacity.

The coolant must be packaged in a 15 mil (minimum) thick heat-sealed plastic bag. Six of these packs, with a total weight of 9.8 kg, will form a case and surround the product (Fig. 2).

<u>RBC Pack</u> -- Red Blood Cell solution is first drawn into an 800 ml PVC primary collection bag (13-15 mil thick, Fenwal 4R1242); glycerol is then added to a final 40% weight per volume concentration. The bag is placed in a plastic overwrap, sealed, and placed in a cardboard case (18 cm long x 14 cm wide x 4.5 cm thick). These individual RBC cases are stacked in four columns, as shown in Figure 3. Special care in packaging is necessary because the plastic bags are fragile at low temperatures. It is important to leave voids in the shipping container to permit air circulation and uniform cooling.

<u>Heat Transfer Mechanism</u> -- Heat gain of frozen RBC solution may be calculated in the temperature range of -80 to -40 ^{o}C by the following equation:

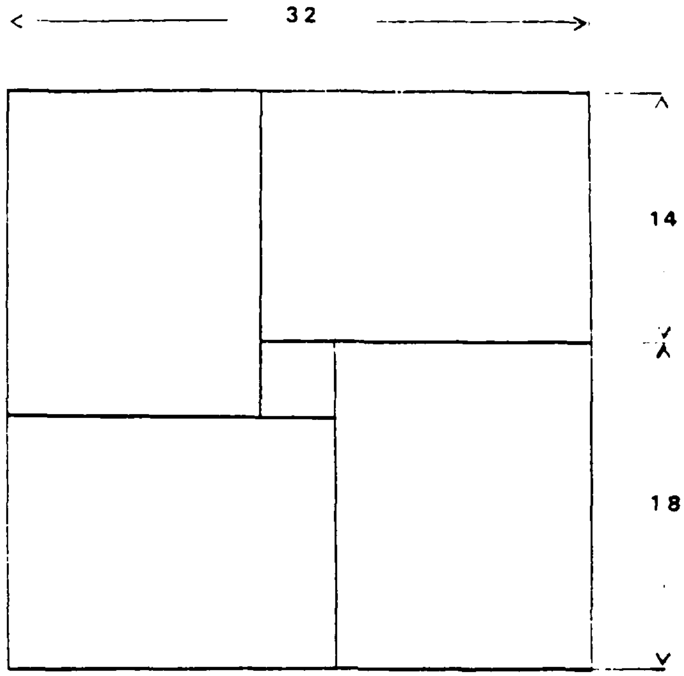


Figure 3. Schematic location of RBC packs inside the storage cavity.

$$Q_b = \int_{-80}^{-40} M_b\ C_b\ dT \qquad (1)$$

where

Q_b: heat gained by frozen RBC solution, J

M_b: total mass of the frozen RBC solution, kg

C_b: specific heat of the frozen RBC solution, J/kg.^{o}C

The heat gain through walls of the shipping container will vary with: the type and thickness of insulation, type of construction, outer and inner material of the container, outside

wall area, and temperature difference between frozen blood and surroundings. The overall coefficient of heat transfer, U, of the wall can be calculated by the following equation:

$$U = \frac{1}{\frac{1}{f_i} + \frac{2\,x_1}{k_1} + \frac{x_2}{k_2} + \frac{1}{f_o}} \qquad (2)$$

where

U = overall heat transfer coefficient, $w/m^2.^oC$

x_1 = thickness of inner/outer fiberboard, m

x_2 = thickness of foamed polyurethane, m

k_1 = thermal conductivity of fiberboard, $w/m.^oC$

k_2 = thermal conductivity of foamed polyurethane, $w/m.^oC$

f_i = inside film or surface conductance, $w/m^2.^oC$

f_o = outside film or surface conductance, $w/m^2.^oC$

After establishing the coefficient of heat transfer (U), the heat gain through the walls of the container, for a duration of 48 hours, is calculated by the basic equation:

$$Q_w = DUA\,\Delta T \qquad (3)$$

where

Q_w = heat leakage, J

D = duration, sec.

A = outside area of container, m^2

ΔT = difference between outside air temperature and mean temperature of the product, ^oC

When the heat transfer rate of the insulated container is known, the amount of cooling required can be estimated with reasonable accuracy from

$$Q_c = Q_w - Q_b \qquad (4)$$

$$Q_c = \int_{-80}^{T_m} M_c\, C_{p_s}\, dT + M_c L + \int_{T_m}^{-40} M_c\, C_{p_l}\, dT \qquad (5)$$

where

Q_c = heat absorbed by coolant, J

T_m = melting point of coolant, ^oC

M_c = total mass of coolant, kg

C_{p_s} = specific heat of solid coolant, $J/kg.^oC$

C_{p_l} = specific heat of liquid coolant, $J/kg.^oC$

L = latent heat of fusion, J/kg

These calculations can be made only when the thermal properties of the frozen RBC solution and materials of the container are known.

Some form of temperature indicator is desirable for the shipment container.

RESULTS AND DISCUSSION

Since the state of life of frozen RBC solution depends on maintaining a temperature between -80 to -40^{o}C, the heat transfer capability in this temperature range is especially crucial. Of all three basic mechanisms of heat transfer, conduction is the most dominant in determining heat transfer within the material. The ability of frozen RBC solution to transport energy by conduction is best characterized in the steady state by its

thermal conductivity, and in the transient state by its thermal diffusivity. Therefore, the thermal properties of frozen blood and its components must be known not only to solve thermodynamic problems involving shipping containers, but also to predict the probability of survival of the various blood cells.

The data for properties of blood that exist exhibit a degree of scatter that for many applications is unacceptable and covers only a small range of temperature. The need for accurate data for blood and blood solutions dictates the development of improved methods of measuring thermophysical properties for the heat transfer analysis of the shipping container.

Furthermore, the specific heat of the favorable coolants is likewise not documented. This lack of information is another obstacle in predicting the heat transfer rate and consequent sizing of the shipper.

The schedule of dimensions for the frozen blood shipping container is presented in Figure 2. The container which accommodates 24 RBC packs weighs 31.2 kg. (68.6 lbs.); the outside dimensions are 0.54m x 0.54m x 0.52m (21 1/2" x 21 1/2" x 20 1/2"). This size and weight are within the standards set in reference 8.

In response to task requirements, Item 5 of SETA Task Directive No. 87-031, the following information is furnished:

a. Several companies manufacture insulated shipment containers for refrigerated temperature sensitive pro-

ducts. These containers essentially consist of a rectangular cardboard box, with 1-3 inches of polystyrene or polyurethane insulation. Most of these manufacturers have used "third ice" to replace wet or dry ice. Third ice is a gel refrigerant composed of various organic ingredients combined with water; it melts near $0^{o}C$. Containers made by Insulated Shipping Containers, Inc., and Polyfoam Packers Corporation show promise and may be modified to ship frozen blood.

b. The primary function of an insulated shipping container is to permit economical control of the environment around the frozen blood packs during transportation. The necessary features are determined by its type, size, weight and use. Among several possible models, the one which consists of insulation and coolant appears to be the most feasible for this purpose. The shipper contains a coolant which surrounds the individual RBC packs. Nonetheless, it is also possible to preserve the blood by putting the coolant inside each RBC pack. If size and weight permit, this will be a more effective configuration.

c. As previously quoted, several nonsublimating organic coolants, solely or in combination, are suitable for this application. Lack of information concerning the specific heat of these materials in both solid and liquid phase creates difficulty in evaluating the sensible heat capacity of the storage box. As a result,

an accurate heat transfer analysis for the effectiveness of the coolants relies on the measurements of specific heat.

d. The scope of this report was restricted to an insulated box with a coolant used for storage and shipment of individual packs of frozen blood. A collapsible containe with the same configuration may suffer from the problem of stacked space due to the thickness of foamed insulation. This kind of container, commercially known as a knockdown (KD) container, has the disadvantage of lower thermal conductivity. The foamed polyurethane which is fully bonded between the inner and outer walls in the solid container cannot be used in the KD container and must be replaced by foamed polystyrene or similar insulation which is less effective (approximately 50% less). A design not using foamed insulation will accommodate the collapsibility criteria, but will suffer economically.

e. The container can accommodate up to 30 RBC packages when "Dense Packing" is employed. A plastic basket or crate which fits in the inner shell is recommended to assist the transfer of the blood packs to and from the freezer.

f. The cost of insulation increases with thickness, both for material and construction. The function of insulation is clear; to reduce energy loss from a surface

operating at a temperature other than ambient. Optimum use of insulation reduces the cost and improves process efficiency. Beyond the optimal economic thickness, additional insulation does not yield the maximum rate of return on investment. Greater insulation thickness also means a larger container or smaller storage space. The restrictions on the size of the blood shipment box along with thermodynamic constraints suggest a 10 cm (4 in.) thick foamed polyurethane for the most efficient pattern. Although the application of foamed insulation may not be the most efficient design, it certainly is the most economical.

g. The frozen blood container may also be used to ship refrigerated blood. While the usual consideration is to keep refrigerated blood from becoming too warm, it is sometimes necessary to keep it from becoming too cold. The coolant used for frozen blood must not be used for shipping or storing refrigerated blood due to the danger of freezing and hemolysis.

CONCLUSIONS

A standard rectangular-shaped shipping container capable of accommodating up to 24 packs of red blood cell solution was shown to be suitable for blood storage and transport. The ability of the unit to maintain RBC packs in the desirable and acceptable temperature range was demonstrated using an insulated box coupled with a coolant.

The unit's size (54 cm X 54 cm X 52 cm) and weight (31.2 kg) make it easy for one individual to carry; yet it is strong enough to survive many trips and inexpensive enough to be discarded.

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